Tutorial on Atomic Oxygen Effects and Contamination

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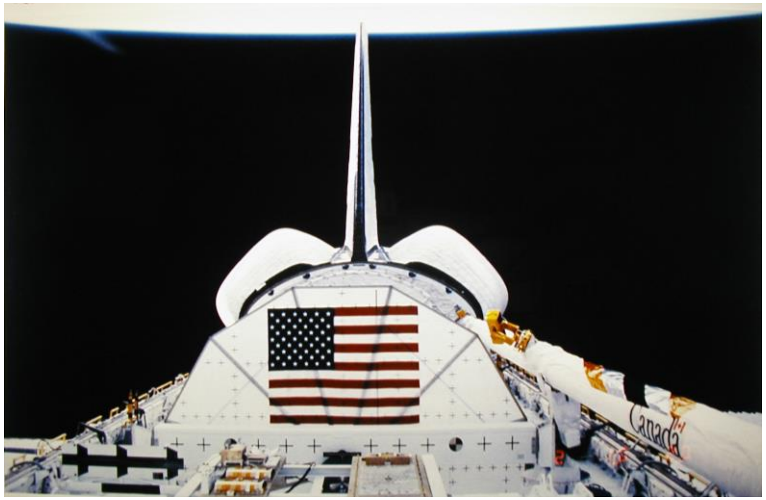
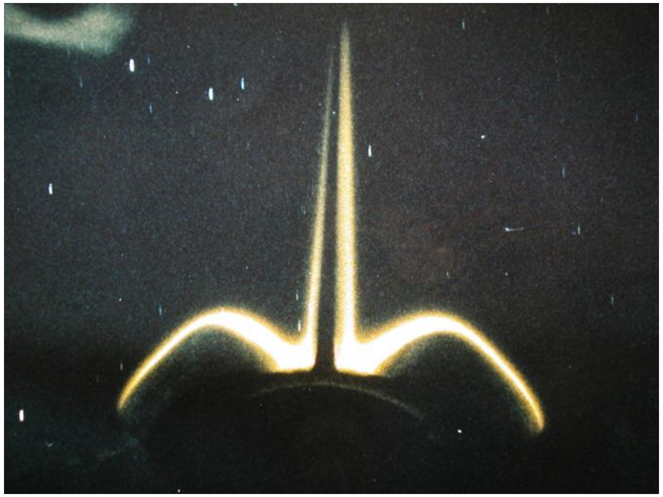
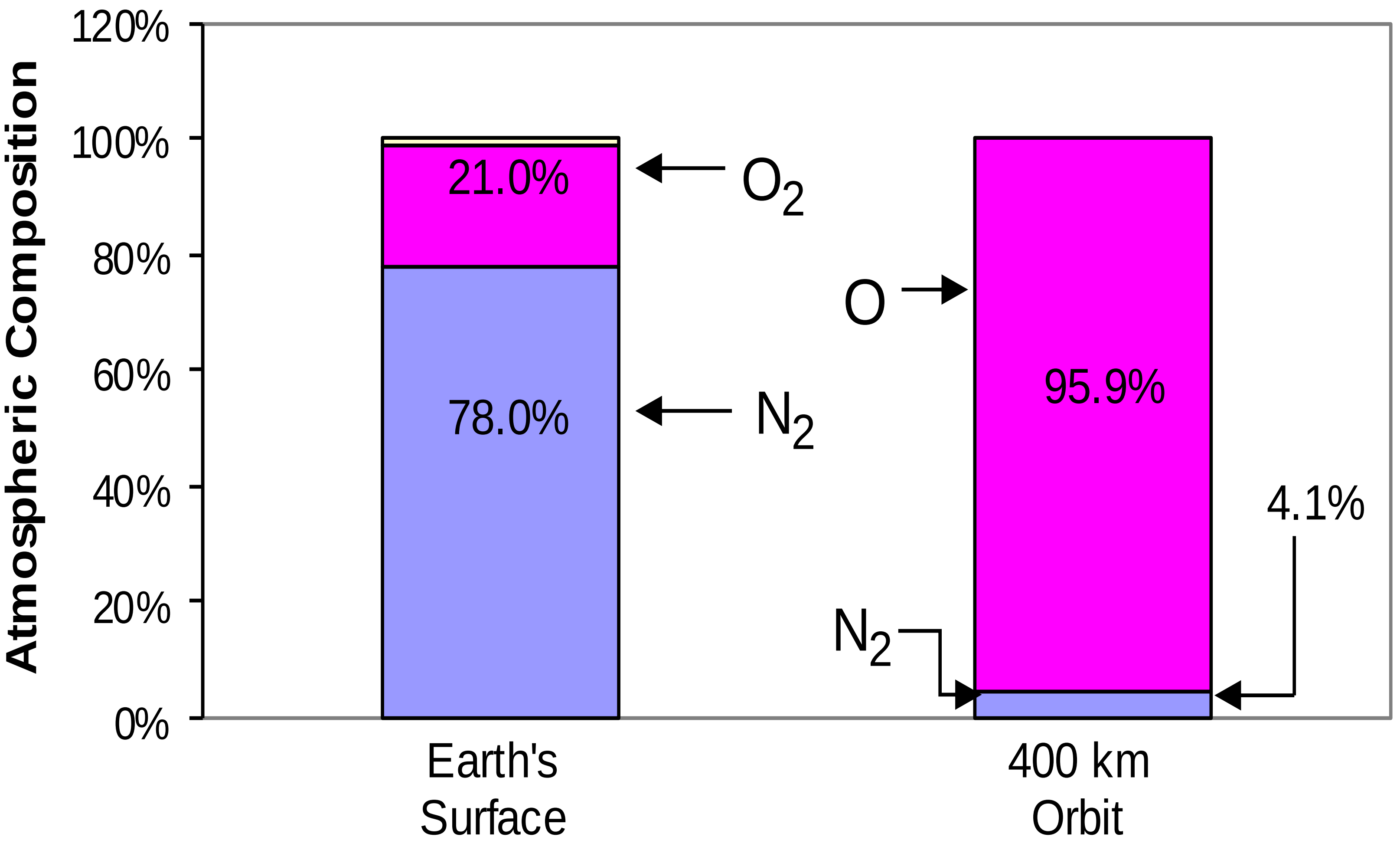
ATOMIC OXYGEN

Environment Interaction Visible on Space Shuttle Tail Section



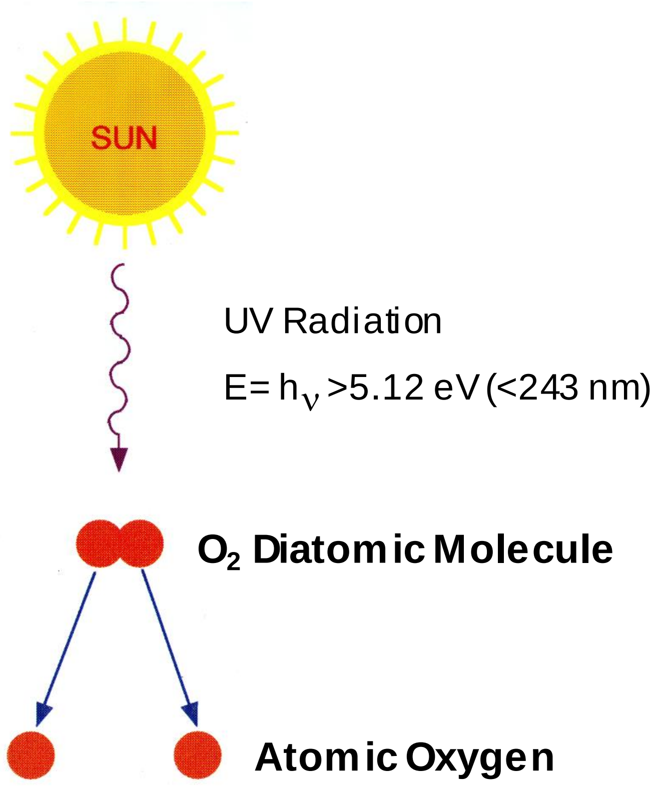


Atmospheric Composition



Atomic Oxygen in Low Earth Orbit

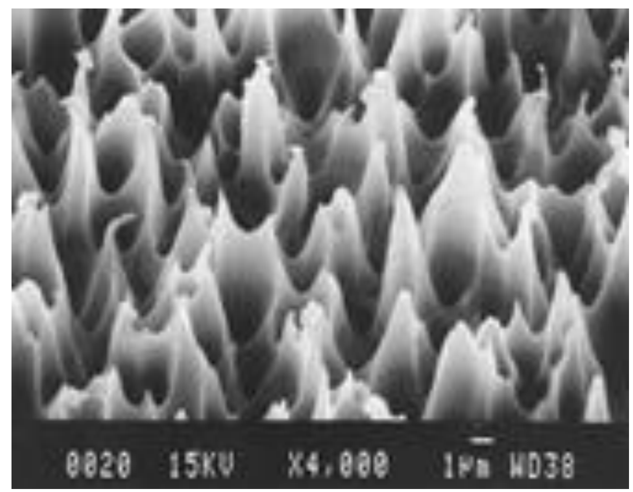
Photodissociation of O_2



- **AO is the predominant species from 180-650 km**
- **Average ram energy ≈ 4.5 eV**

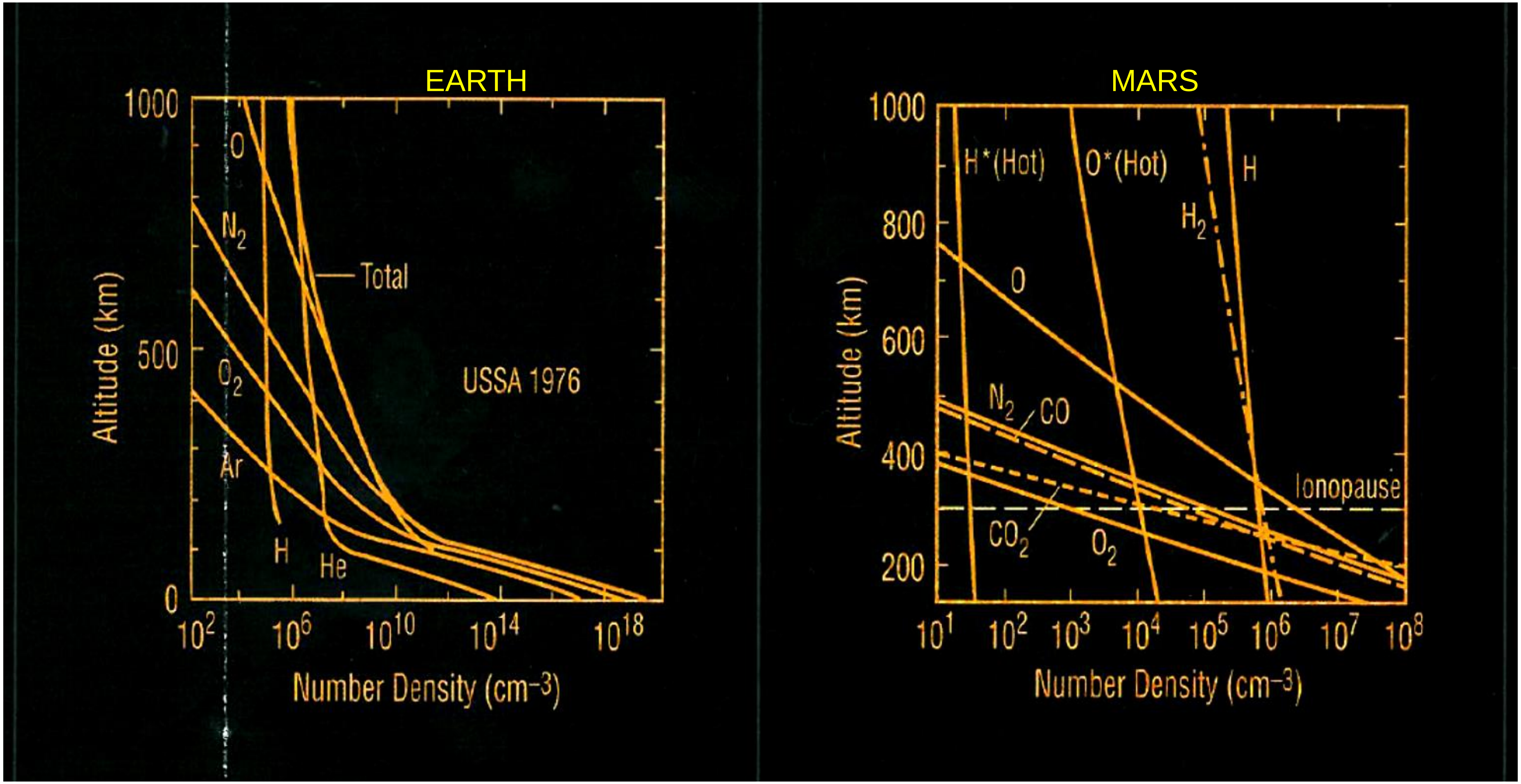
LDEF Spacecraft CTFE after

8.99×10^{21} atoms/cm^2



Polychlorotrifluoroethylene (CTFE)

Atmospheric Composition Comparison Between Earth and Mars



Graphs Courtesy of NASA JPL

Composition of Mars Atmosphere

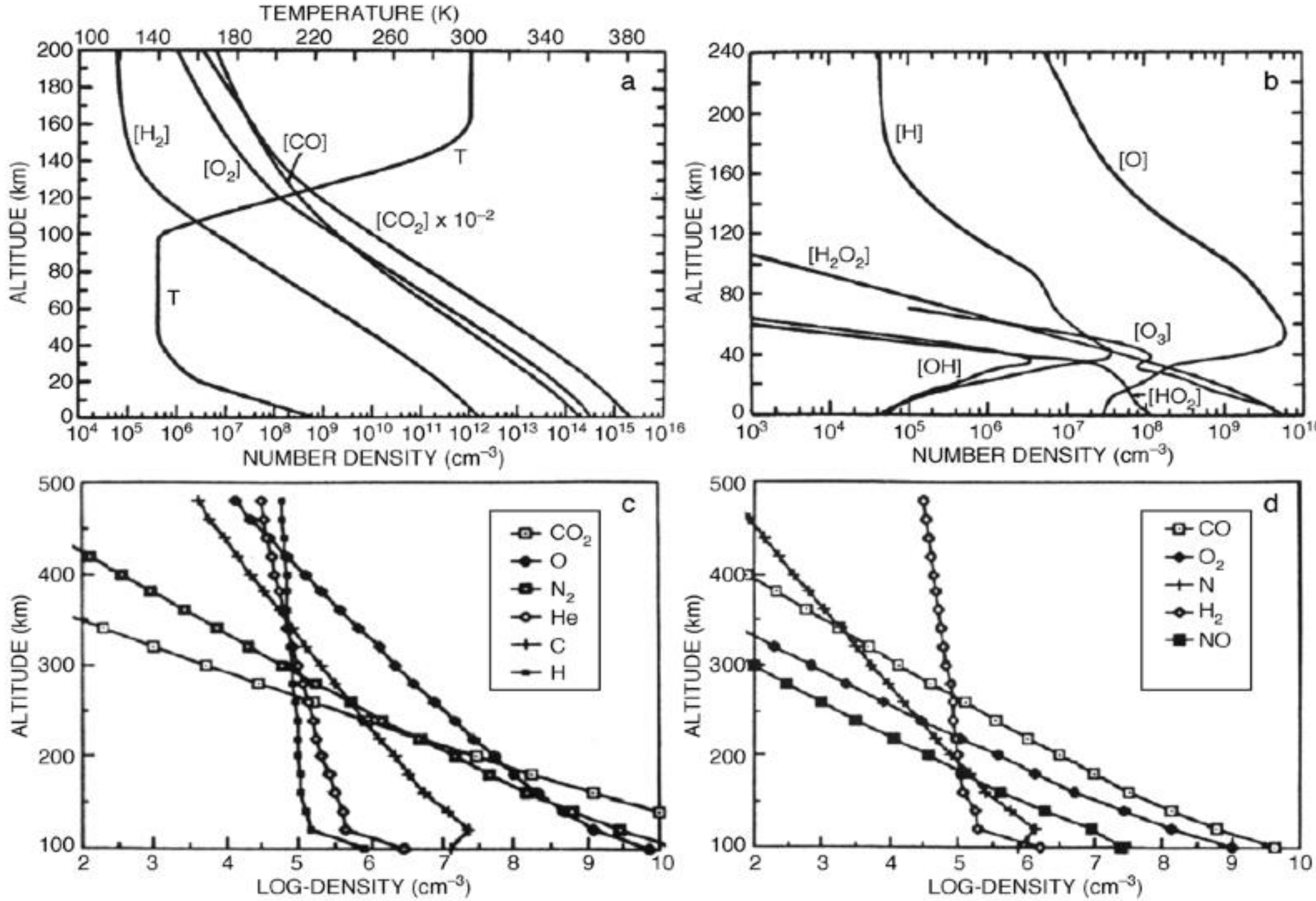
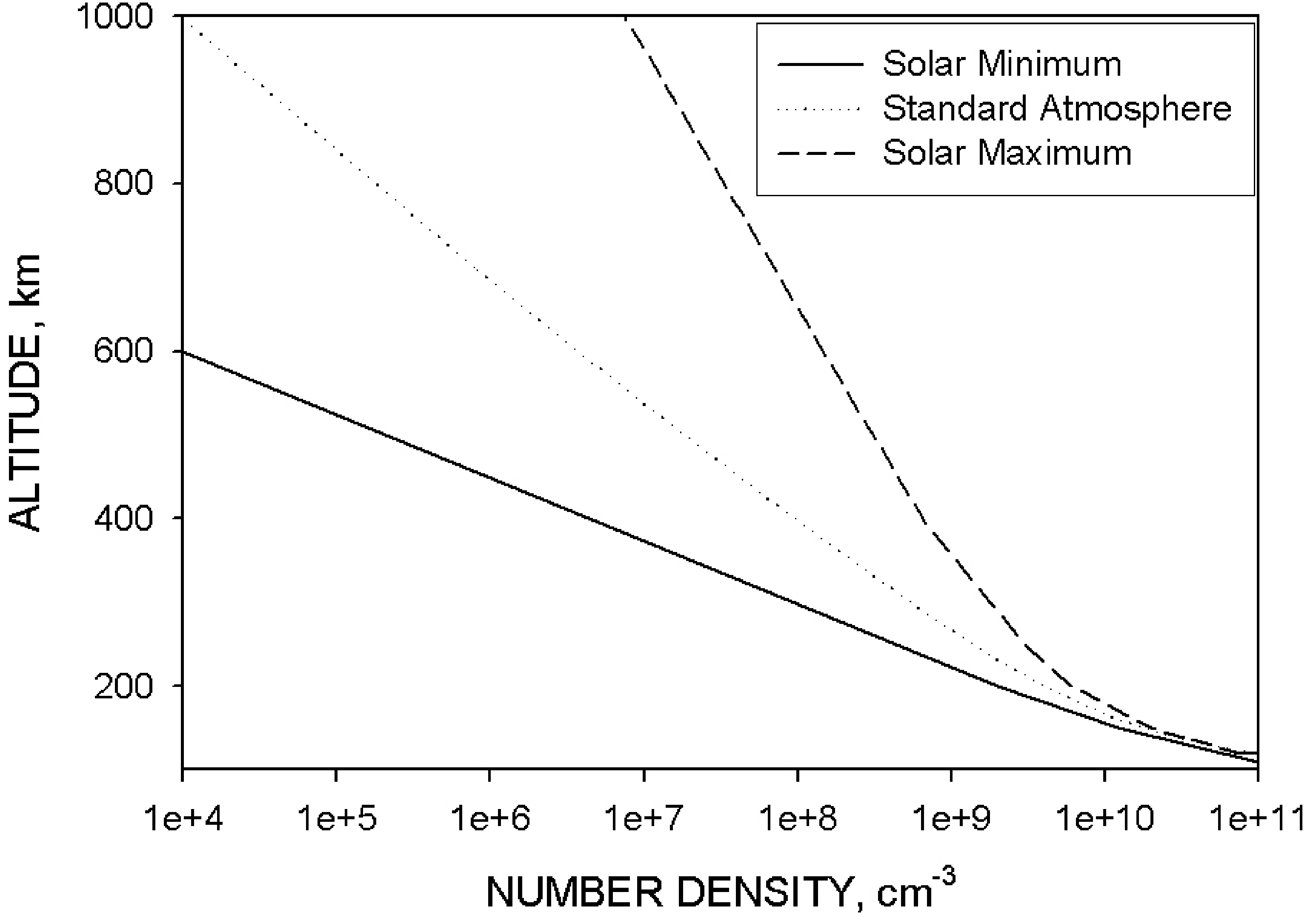


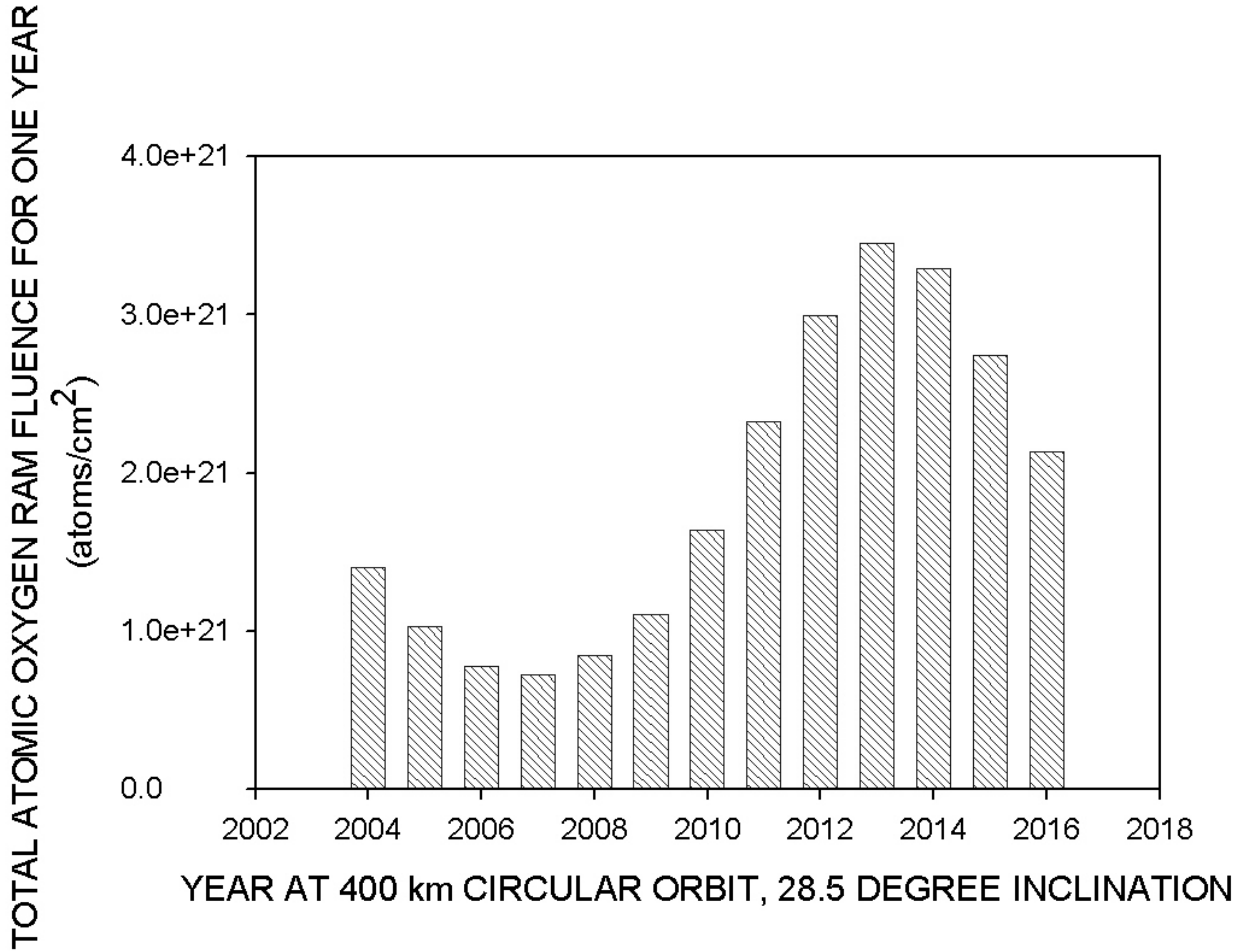
Figure 4-2. Martian Atmospheric Density Profiles for Various Constituents. a) CO_2, CO, O_2, and H_2 in an altitude range between 0 and 200 km, b) O, H, OH, H_2O_2, and O_3 from 0 to 240 km, c) CO_2, O, N_2, He, C, and H between 100 and 500 km and d) CO, O_2, N, H_2, and NO between 100 and 500 km.

Graphs Courtesy of Hank Garrett at NASA JPL

Atomic Oxygen Earth Atmosphere Number Density Dependence Upon Solar Activity

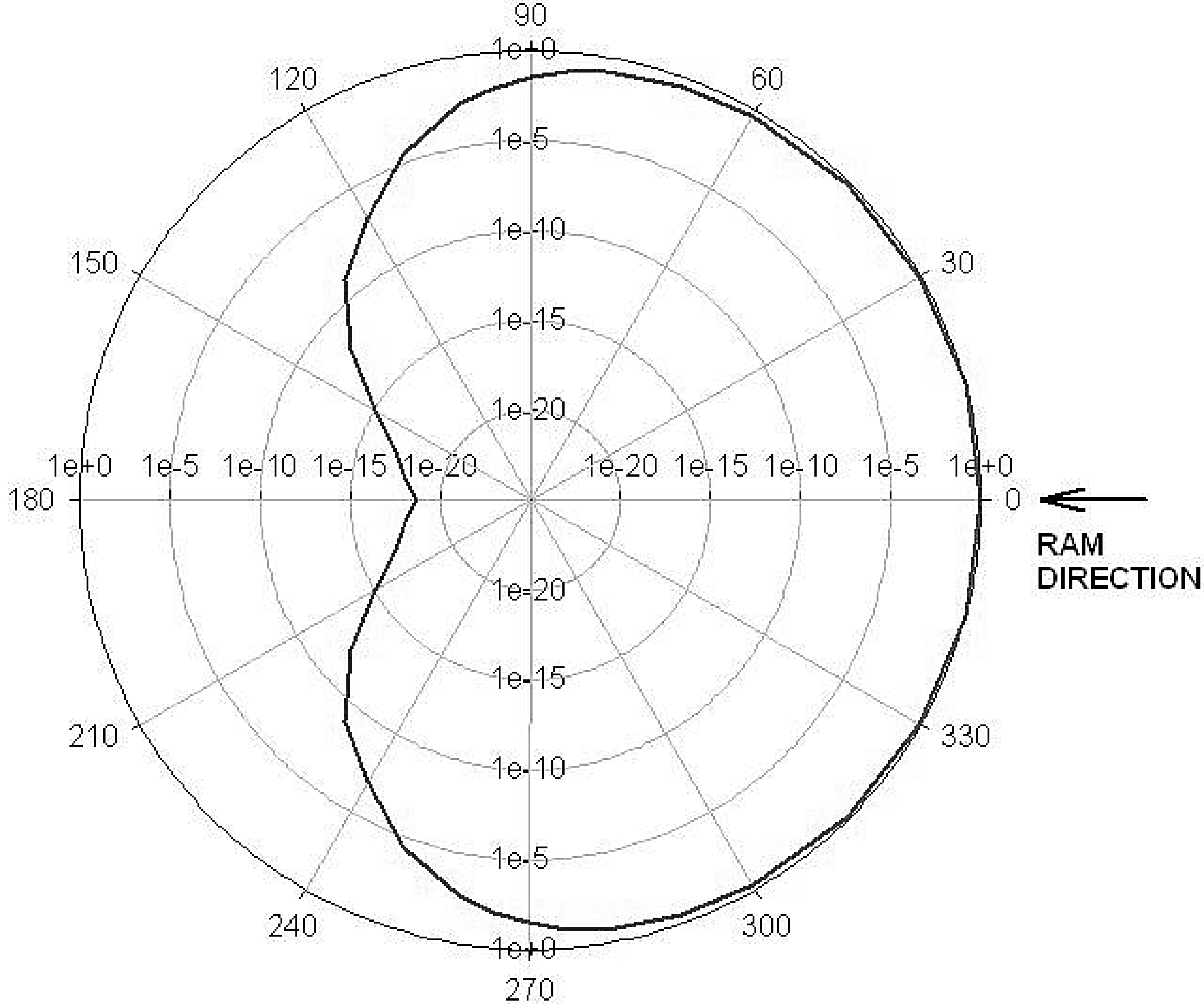


Solar Cycle Caused Variation in Level of Atomic Oxygen in Low Earth Orbit at 400 km

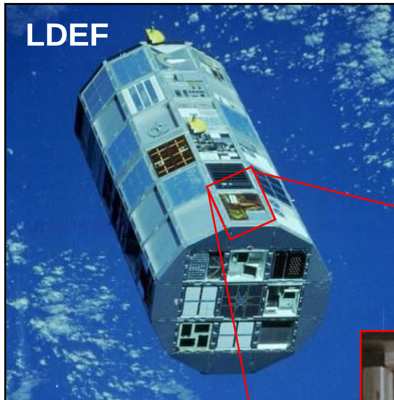


Logarithmic Polar Plot of Atomic Oxygen Arrival Flux

(400 km Earth orbit at 28.5º inclination and 1000 K thermosphere)



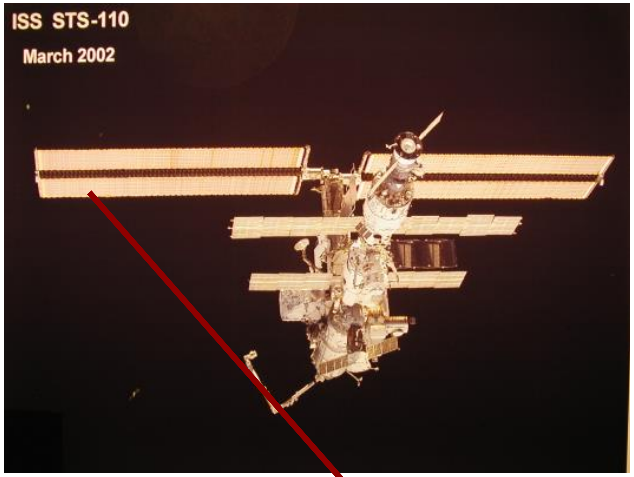
So What Can Atomic Oxygen Do to Spacecraft?

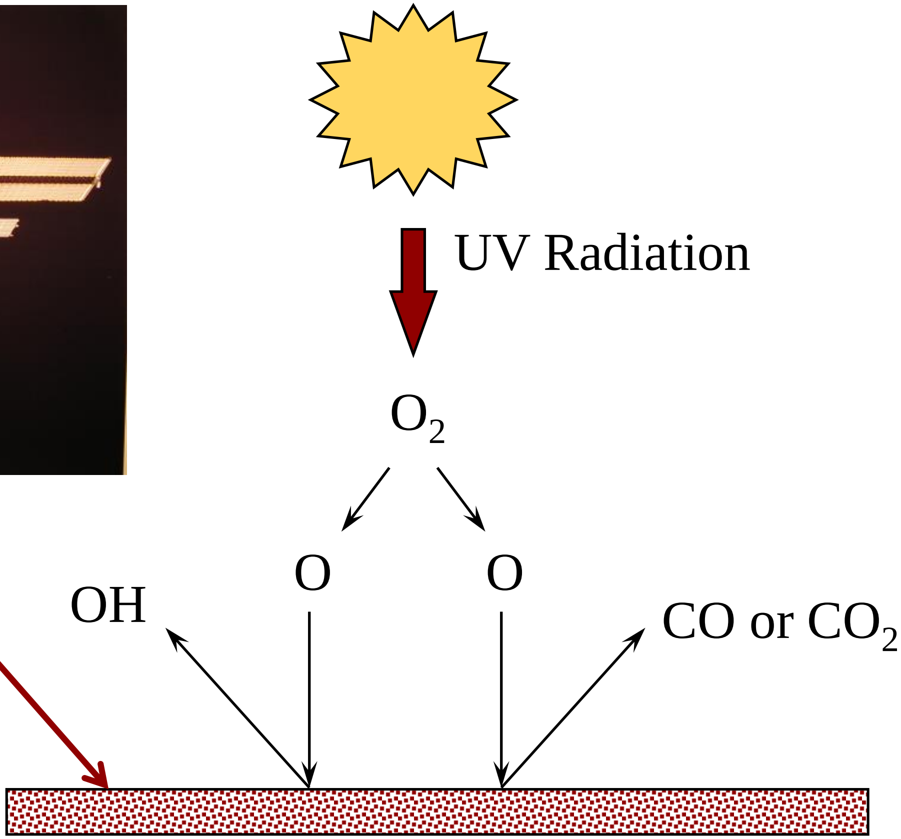


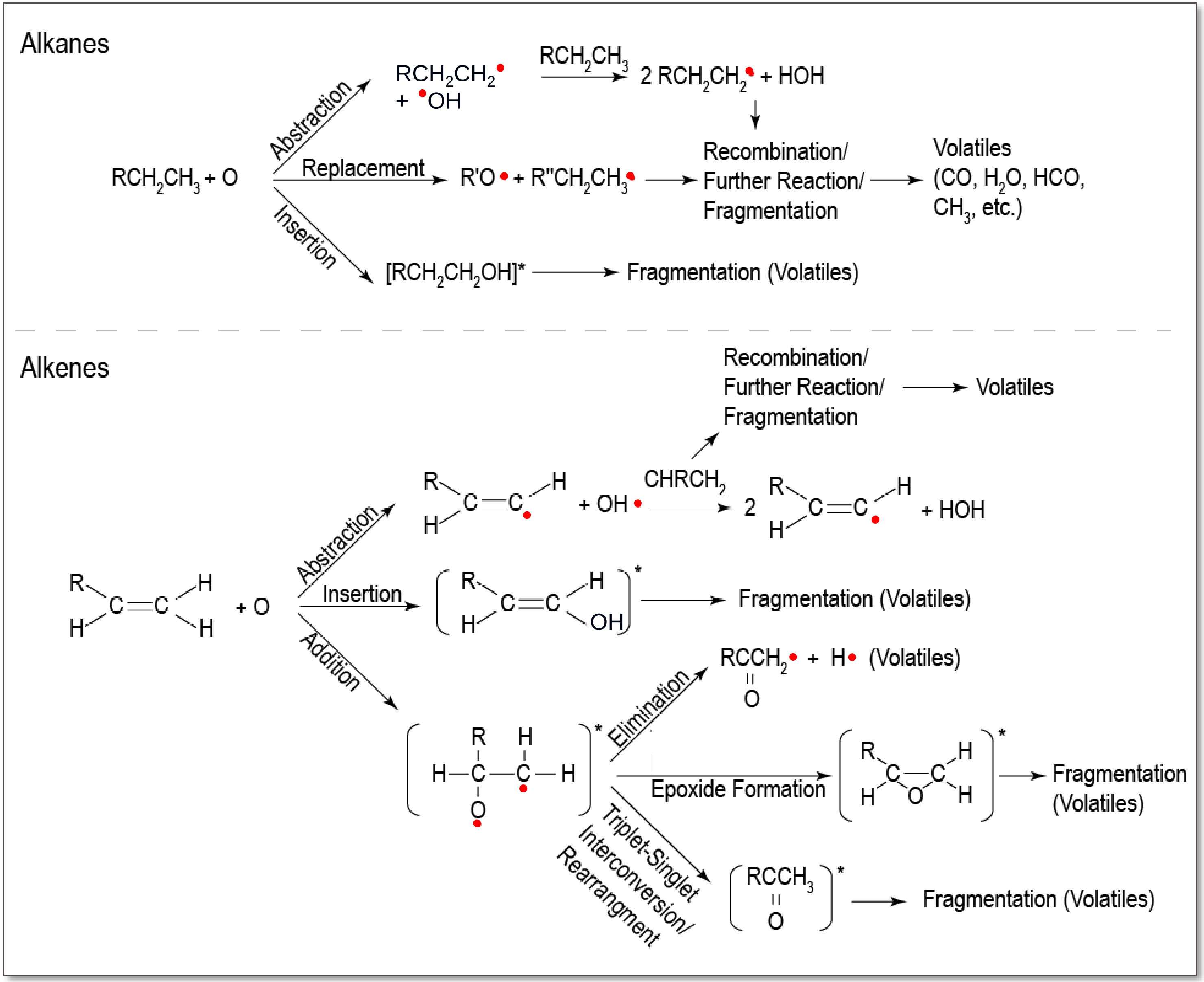
Prior to Flight

After 5.8 years in LEO

Basic Atomic Oxygen Interaction with Organic Surfaces





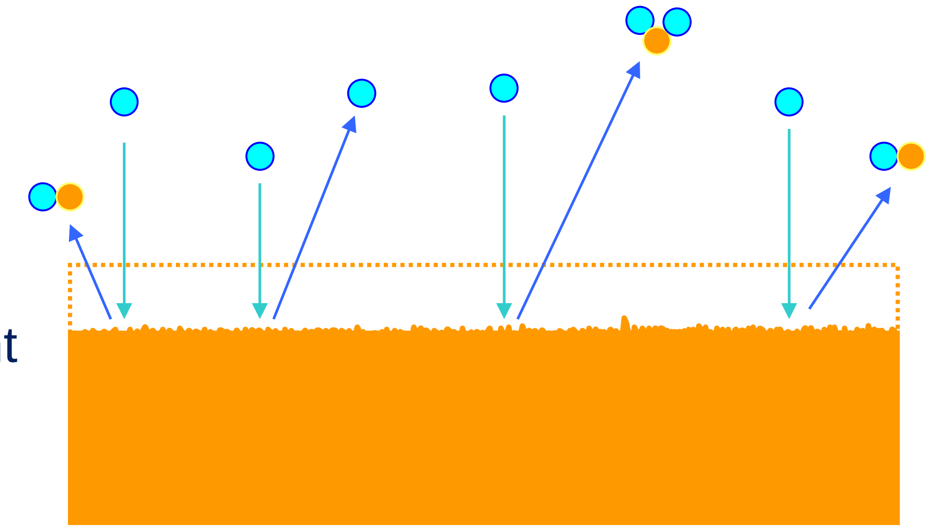


Alkanes
Abstraction
Replacement
Insertion
RCH2CH3 + O
RCH2CH2• + •OH
RCH2CH3
2 RCH2CH2• + HOH
R'O• + R"CH2CH3•
Recombination/ Further Reaction/ Fragmentation
Volatiles (CO, H2O, HCO, CH3, etc.)
[RCH2CH2OH]*
Fragmentation (Volatiles)
Alkenes
Abstraction
Insertion
Addition
+ O
+ OH•
CHRCH2
+ HOH
Recombination/ Further Reaction/ Fragmentation
Volatiles
Fragmentation (Volatiles)
Elimination
RCCH2• + H• (Volatiles)
Epoxide Formation
Fragmentation (Volatiles)
Triplet-Singlet Interconversion/ Rearrangment
RCCH3
Fragmentation (Volatiles)

Atomic Oxygen Erosion Yield (E_y)

E_y is the **volume loss** per incident **oxygen atom**

(cm^3/atom)



Ey based on Mass Loss Measurements

Erosion Yield (E_y) of Sample

$$E_y = \frac{\Delta M_s}{A_s \rho_s F_k}$$

where:

ΔM_s =	**mass loss of polymer sample**
A_s =	**area of polymer sample**
ρ_s =	**density of sample**
F_k =	**AO fluence measured by Kapton H witness samples**

Atomic Oxygen Fluence

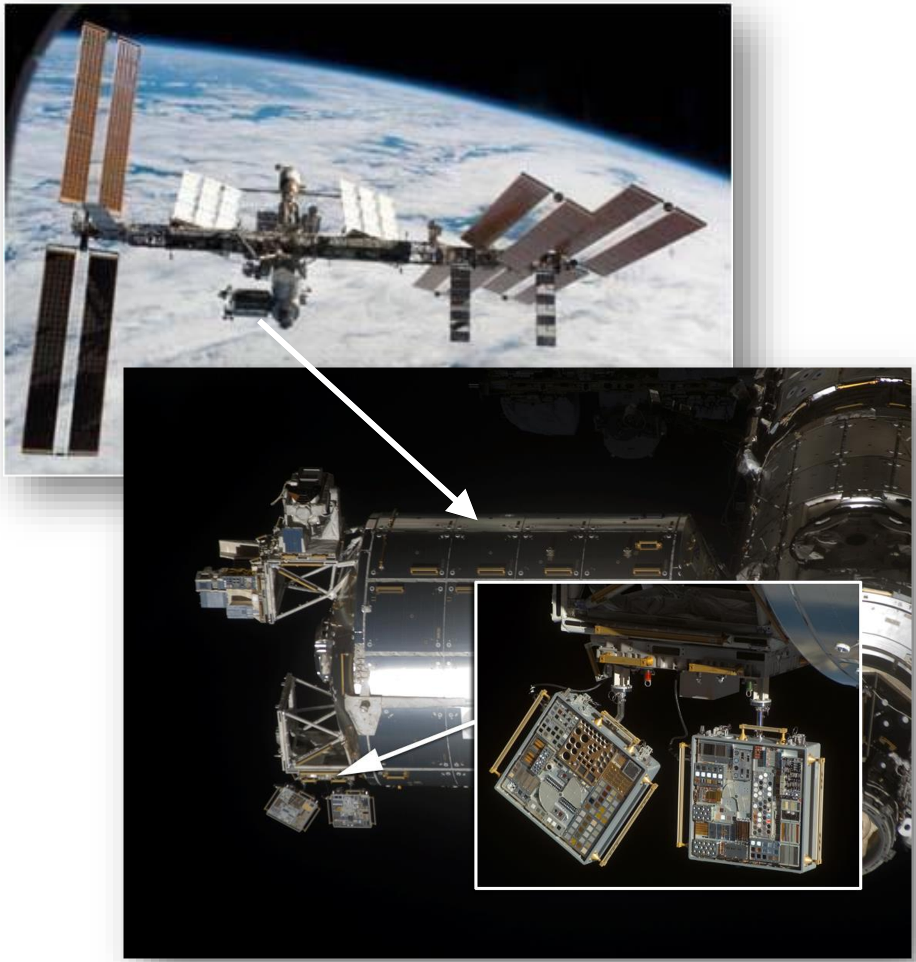
$$F_k = \frac{\Delta M_k}{A_k \rho_k E_k}$$

where:

ΔM_k =	**mass loss of Kapton H witness**
A_k =	**area of Kapton H witness**
ρ_k =	**density of Kapton H sample (1.427 grams/cm^3)**
E_k =	**erosion yield of Kapton H (3.0×10^{-24} cm^3/atom)**

Material Tests in Low Earth Orbit (LEO) for Environment Interactions

Materials International Space Station Experiment (MISSE)

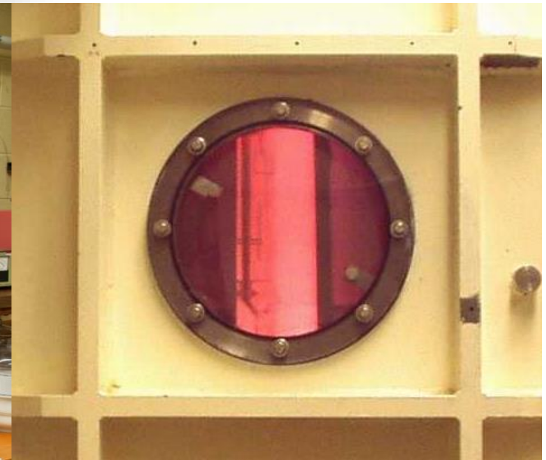


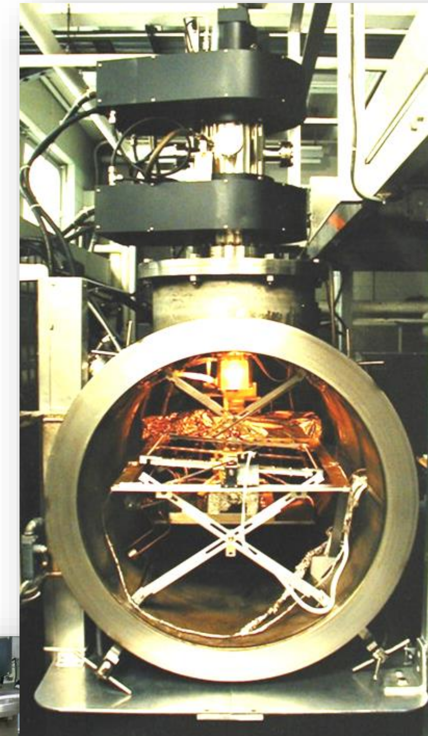
Long Duration Exposure Facility (LDEF)

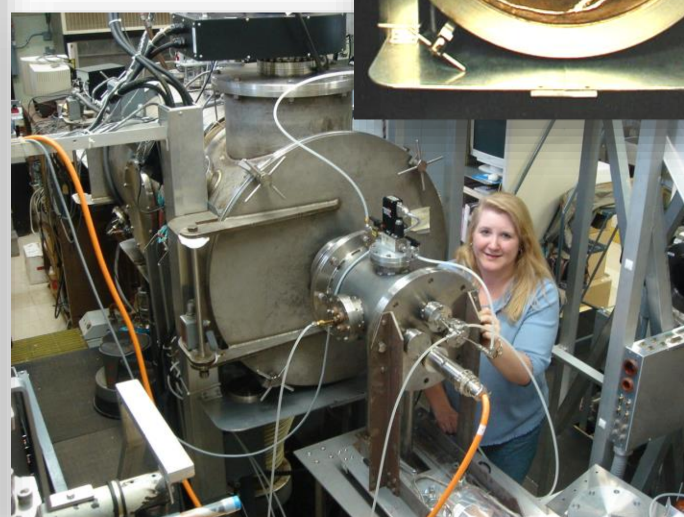
Atomic Oxygen Erosion Yields of Polymers Flown on MISSE-2 (PEACE)

Material	Abbrev.	Ey (cm^3/atom)	Ey Uncertainty (%)	Material	Abbrev.	Ey (cm^3/atom)	Ey Uncertainty (%)
Acrylonitrile butadiene styrene	ABS	1.09E-24	2.7	Polyamide 6 or nylon 6	PA 6	3.51E-24	2.7
Cellulose acetate	CA	5.05E-24	2.7	Polyamide 66 or nylon 66	PA 66	1.80E-24	12.6
Poly-(p-phenylene terephthalamide)	PPD-T (Kevlar)	6.28E-25	2.6	Polyimide	PI (CP1)	1.91E-24	2.8
Polyethylene	PE	*3.74E-24*	2.6	Polyimide (PMDA)	PI (Kapton H)	3.00E-24	2.7
Polyvinyl fluoride	PVF (Tedlar)	3.19E-24	2.6	Polyimide (PMDA)	PI (Kapton HN)	2.81E-24	2.6
Crystalline polyvinylfluoride w/white pigment	PVF (White Tedlar)	1.01E-25	4.1	Polyimide (BPDA)	PI (Upilex-S)	9.22E-25	3.0
Polyoxymethylene; acetal; polyformaldehyde	POM (Delrin)	9.14E-24	3.1	Polyimide (PMDA)	PI (Kapton H)	3.00E-24	2.6
Polyacrylonitrile	PAN	1.41E-24	3.3	High temperature polyimide resin	PI (PMR-15)	*3.02E-24*	2.6
Allyl diglycol carbonate	ADC (CR-39)	*6.80E-24*	2.6	Polybenzimidazole	PBI	*2.21E-24*	2.6
Polystyrene	PS	3.74E-24	2.7	Polycarbonate	PC	4.29E-24	2.7
Polymethyl methacrylate	PMMA	*5.60E-24*	2.6	Polyetheretherkeytone	PEEK	2.99E-24	4.5
Polyethylene oxide	PEO	1.93E-24	2.6	Polyethylene terephthalate	PET (Mylar)	3.01E-24	2.6
Poly(p-phenylene-2 6-benzobisoxazole)	PBO (Zylon)	1.36E-24	6.0	Chlorotrifluoroethylene	CTFE (Kel-f)	8.31E-25	2.6
Epoxide or epoxy	EP	4.21E-24	2.7	Halar ethylene-chlorotrifluoroethylene	ECTFE (Halar)	1.79E-24	2.6
Polypropylene	PP	2.68E-24	2.6	Tetrafluorethylene-ethylene copolymer	ETFE (Tefzel)	9.61E-25	2.6
Polybutylene terephthalate	PBT	9.11E-25	2.6	Fluorinated ethylene propylene	FEP	2.00E-25	2.7
Polysulphone	PSU	2.94E-24	3.2	Polytetrafluoroethylene	PTFE	1.42E-25	2.6
Polyeurethane	PU	1.56E-24	2.9	Perfluoroalkoxy copolymer resin	PFA	1.73E-25	2.7
Polyphenylene isophthalate	PPPA (Nomex)	1.41E-24	2.9	Amorphous Fluoropolymer	AF	1.98E-25	2.6
Graphite	PG	4.15E-25	10.7	Polyvinylidene fluoride	PVDF (Kynar)	1.29E-24	2.7
Polyetherimide	PEI	*3.31E-24*	2.6	*Ey > this value because sample stack was partially or fully eroded through			

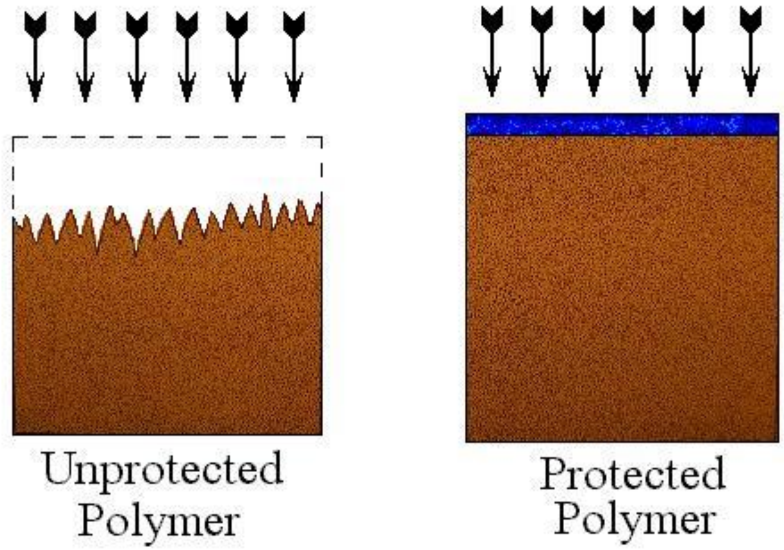
Material Testing in an Atomic Oxygen Environment Using Ground-Based Systems



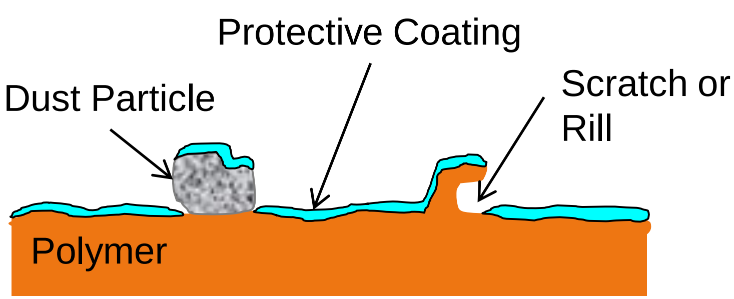




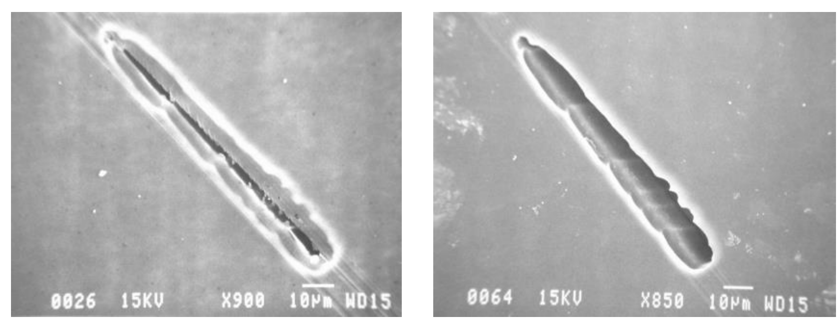
Issues With Protective Coatings



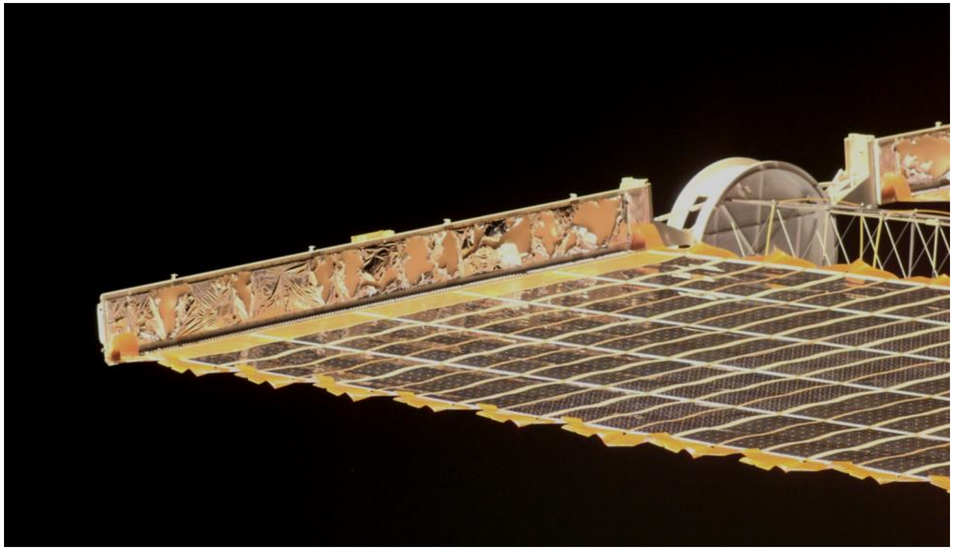
Imperfections in Thin Film Coatings

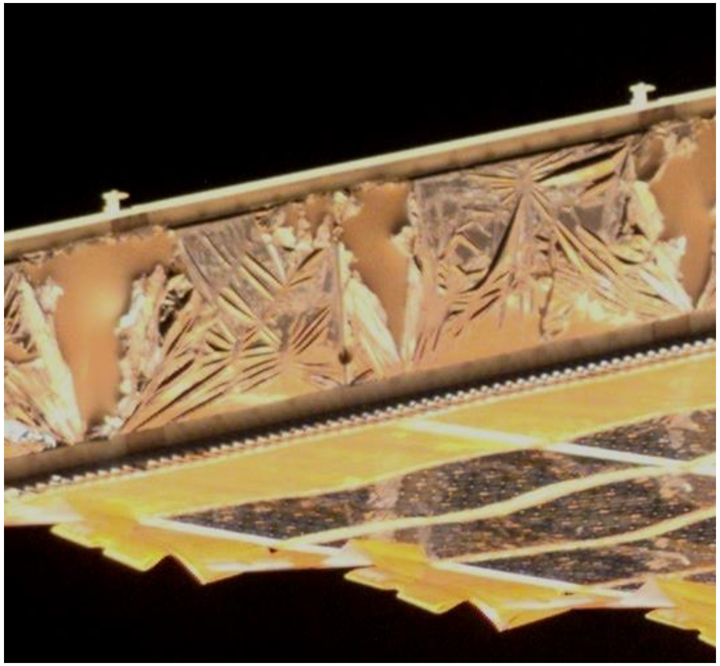


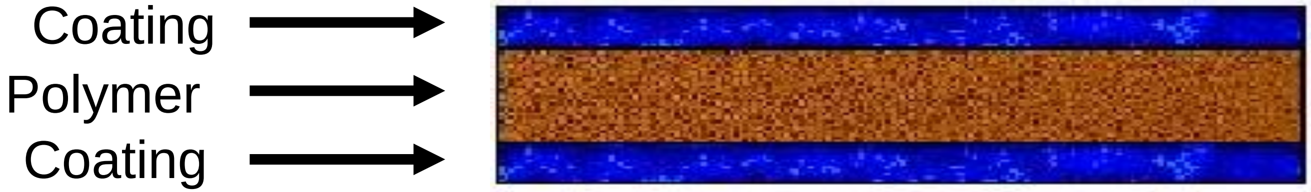
Aluminized Kapton Flown on LDEF



Blanket Box Cover Failure of Aluminized Kapton Observed on ISS

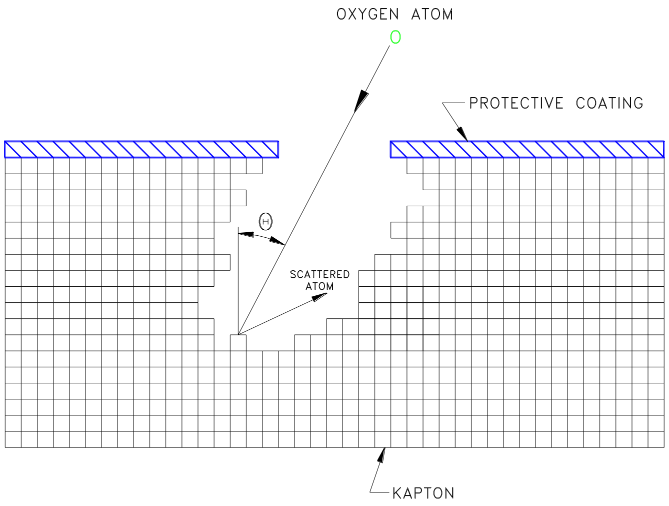


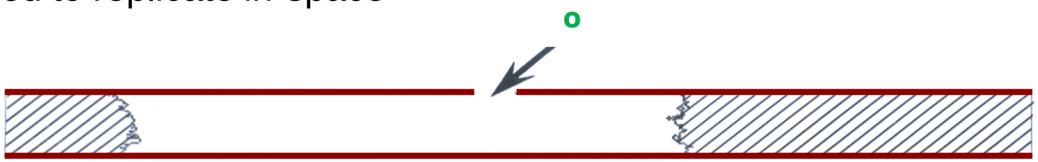




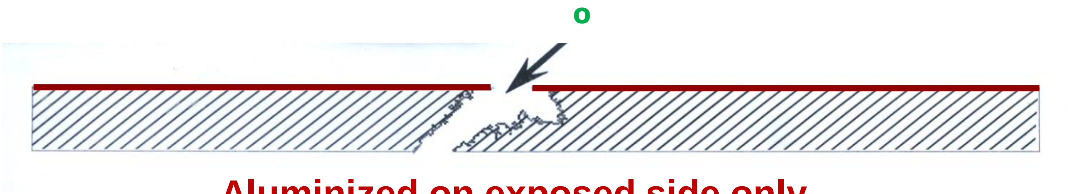
Monte Carlo Computational Model Predictions

- 2-D Computational modeling of atomic oxygen erosion of polymers based on observed in-space results
- Takes into account:
  - Energy dependence of reaction probability
  - Angle of impact dependence on reaction probability
  - Thermalization of scattered oxygen atoms
  - Partial recombination at surfaces
  - Atomic oxygen scattering distribution functions
- Modeling parameters tuned to replicate in-space erosion





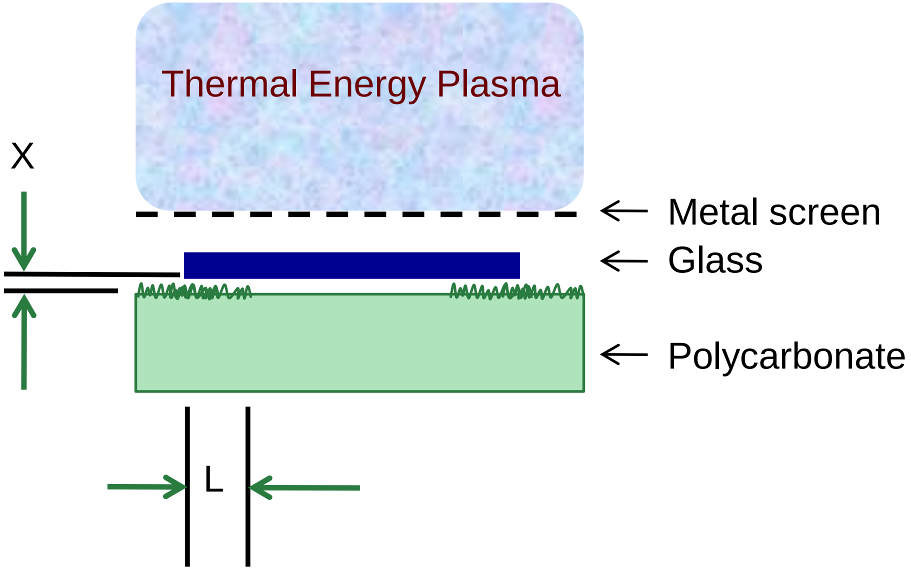
Aluminized on both sides



Aluminized on exposed side only

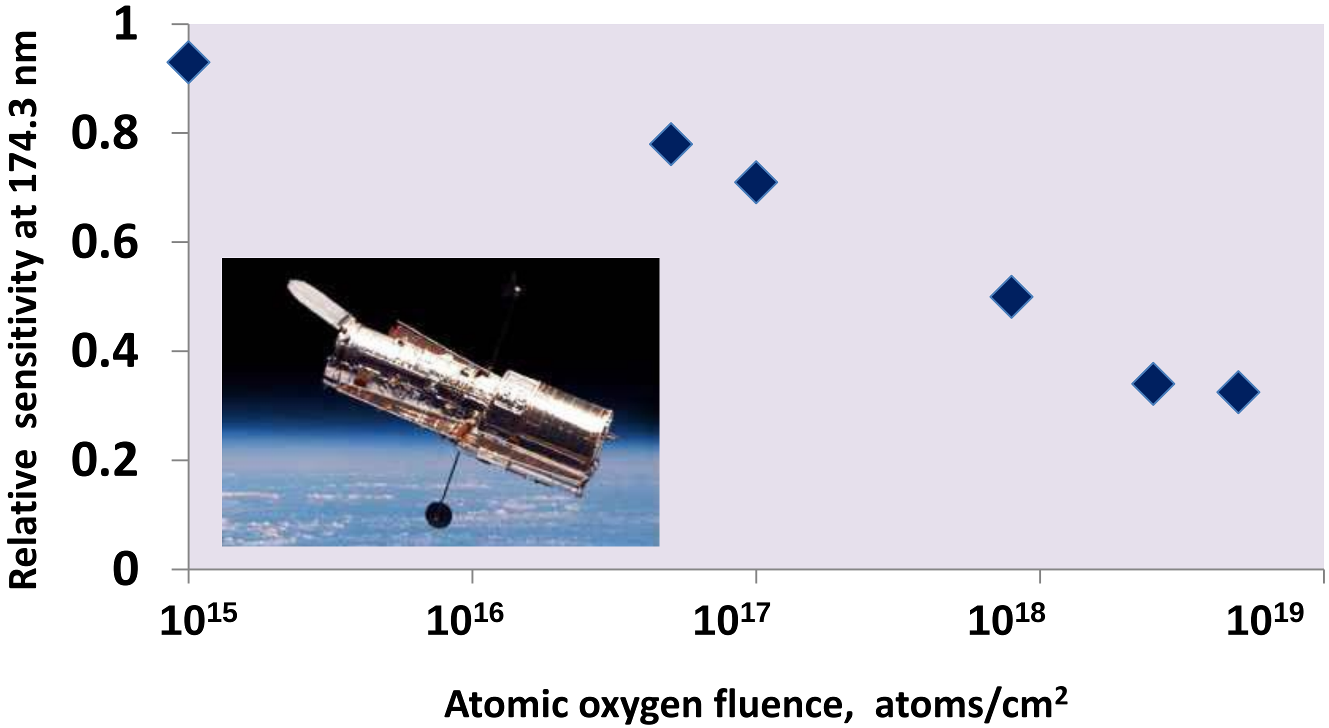
Atomic Oxygen Scattering

12 inch diameter
polycarbonate window



$L/X \cong 165$

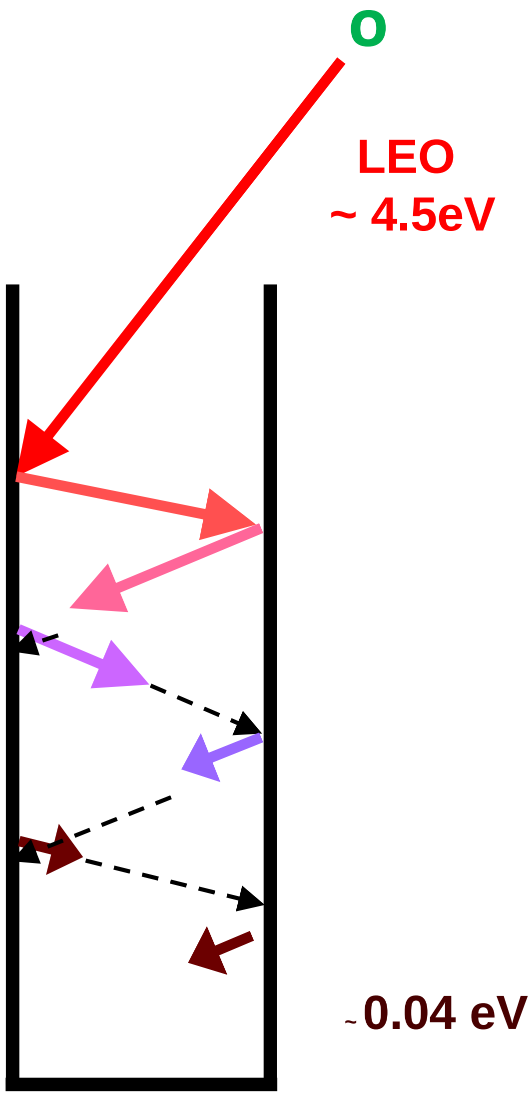
Change in Sensitivity of Cosmic Origins Spectrograph on Hubble Space Telescope



Experienced a far UV sensitivity decline ranging from 3-15%/year

(based on data from June 2009 through mid-February 2010)

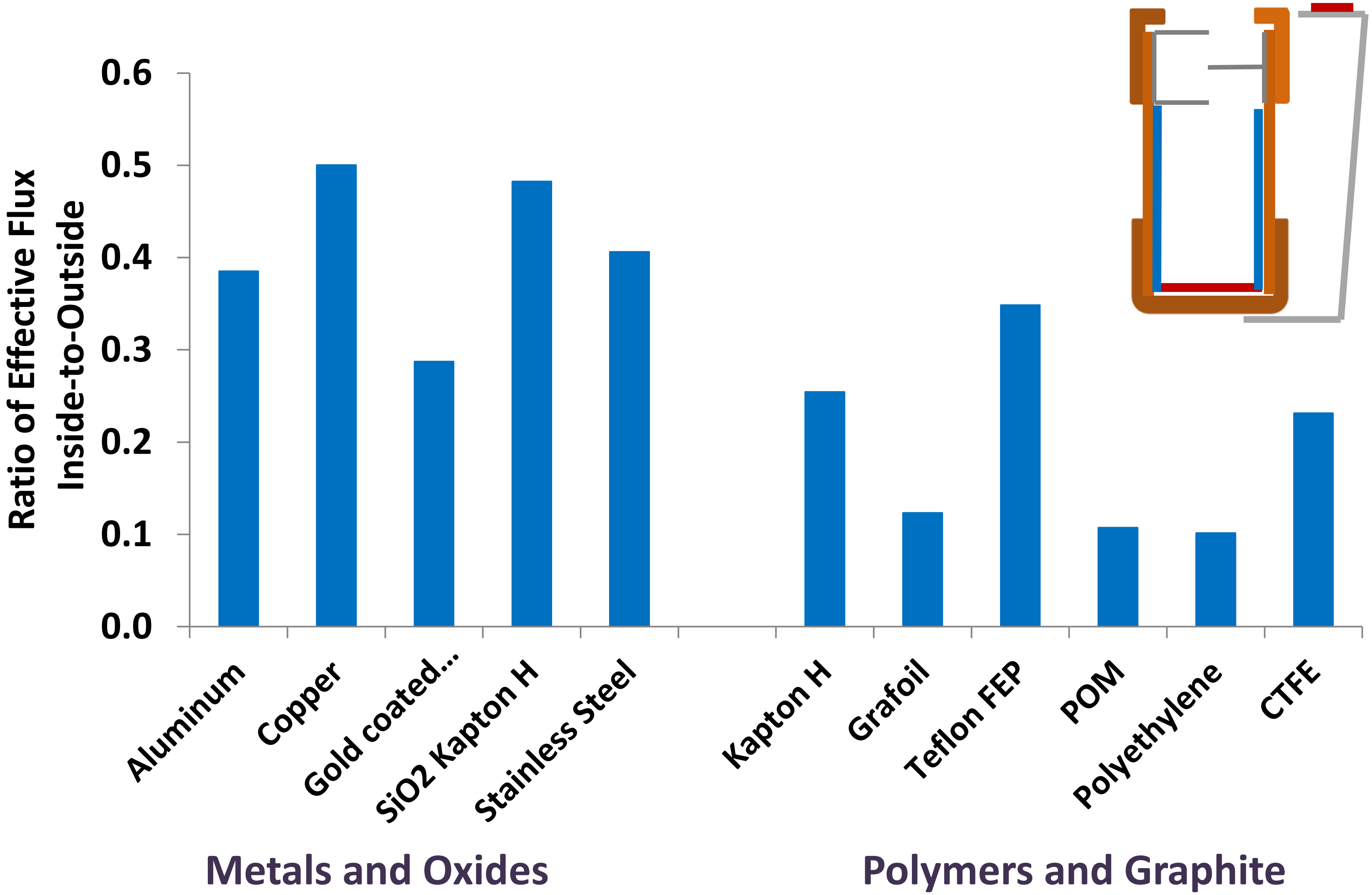
Scattering and Thermal Accommodation of Low Earth Orbital Atomic Oxygen



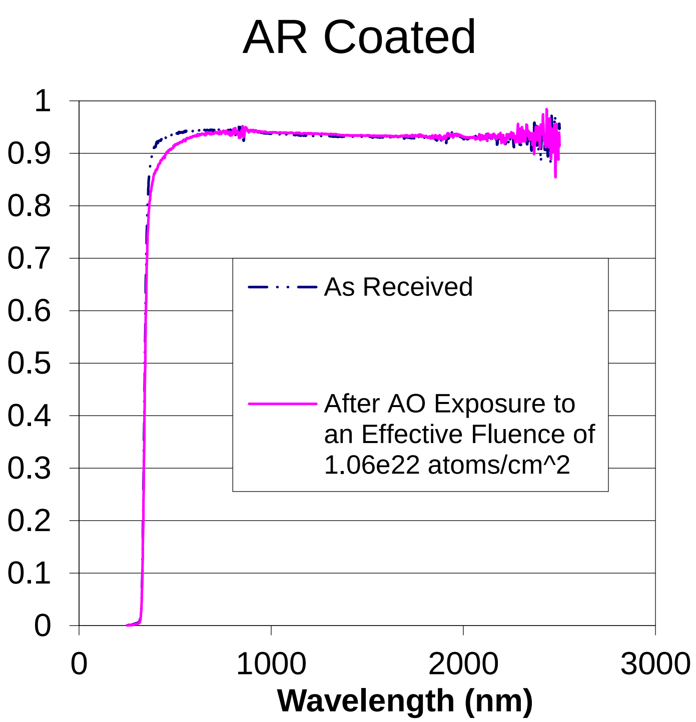
Possible Events Upon Impact:

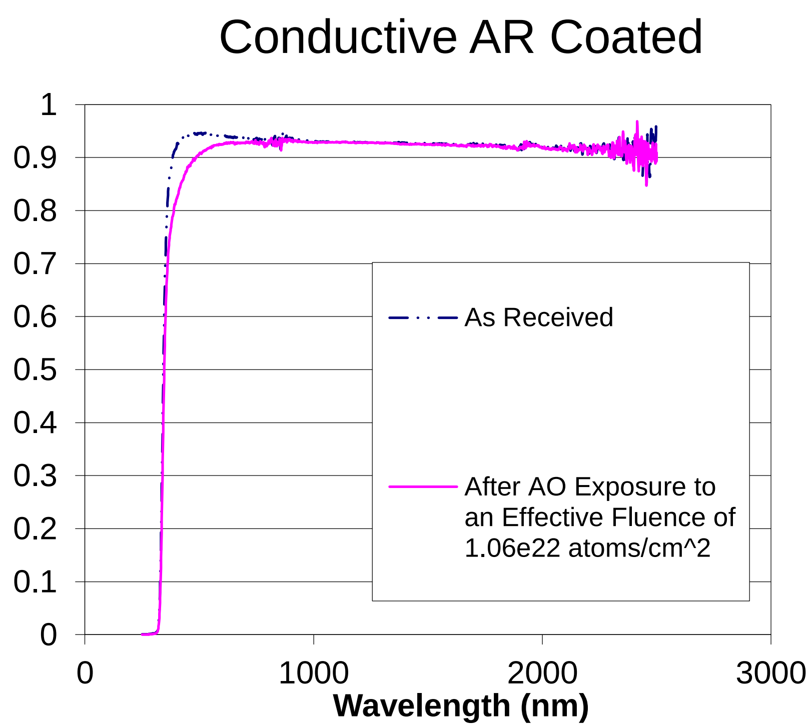
- Reaction
- Recombination
- Scattering
- Partial thermal accommodation
- Ejection out the entrance

Test of Mock Aperture with Various Types of Liners



Total Transmittance as a Function of Wavelength for Coverglass Prior to and After Exposure to Atomic Oxygen

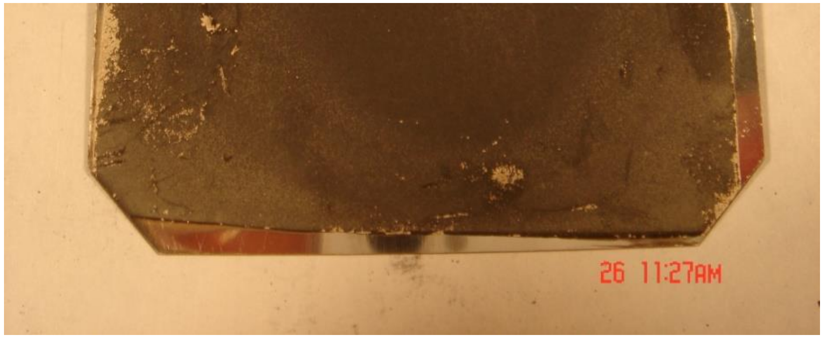




Mirrored Silver Back of Solar Cell Prior to and After Exposure to Atomic Oxygen

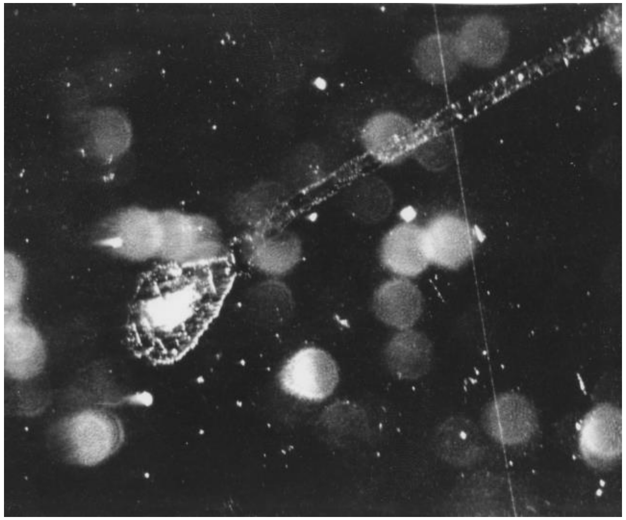
As Received

After Exposure to an AO Effective Fluence of 2×10^{21} atoms/cm^2

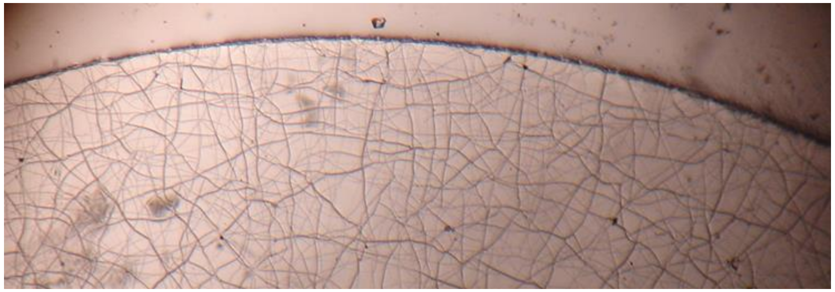


Oxidative Cracking of Silicone

DC 93-500 Silicone
Exposed to LEO Atomic Oxygen on STS-46
Fluence = 2.3×10^{20} atoms/cm^2

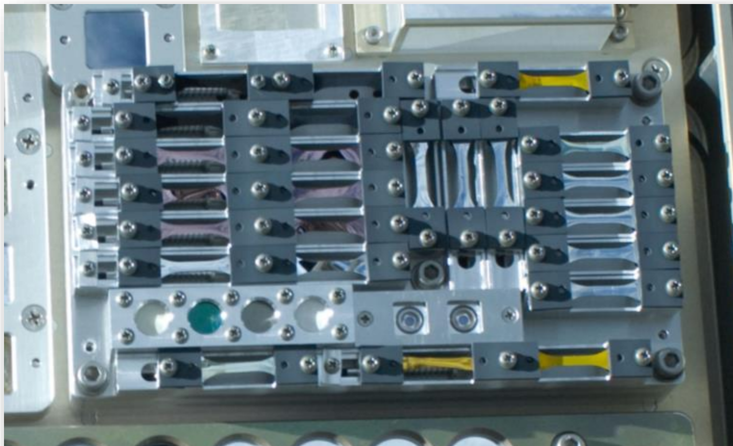


Pre-flight **Post-flight**



Stress Dependent Atomic Oxygen Erosion of Black Kapton XC

Polymers Exposed Under Stress on MISSE 6



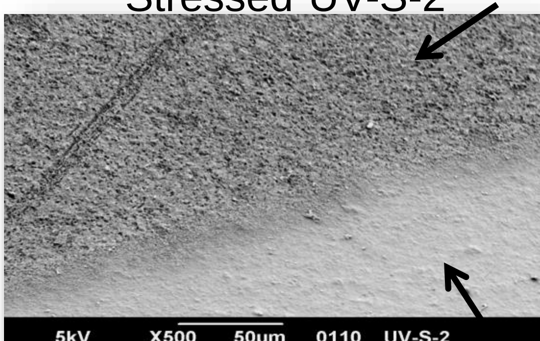
Stressed (left) and Unstressed (right) Black Kapton XC

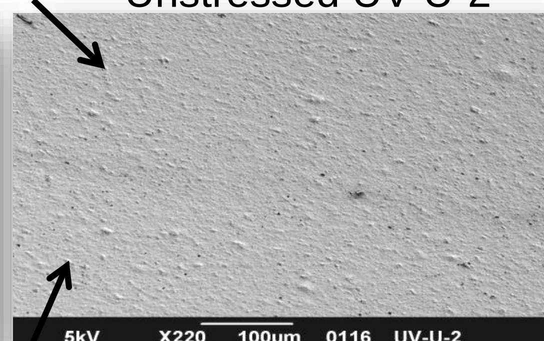
- Stress level: Force/Area = ~4000psi (2.76e7 N/m^2)
- Strain = Stress/Modulus = 4000 psi/480000 psi (3.3e9 N/m^2) = ~0.008
- For Kapton XC this represents ~3 % of the maximum strain and ~24% of the tensile strength

Stressed UV-S-2

Exposed

Unstressed UV-U-2





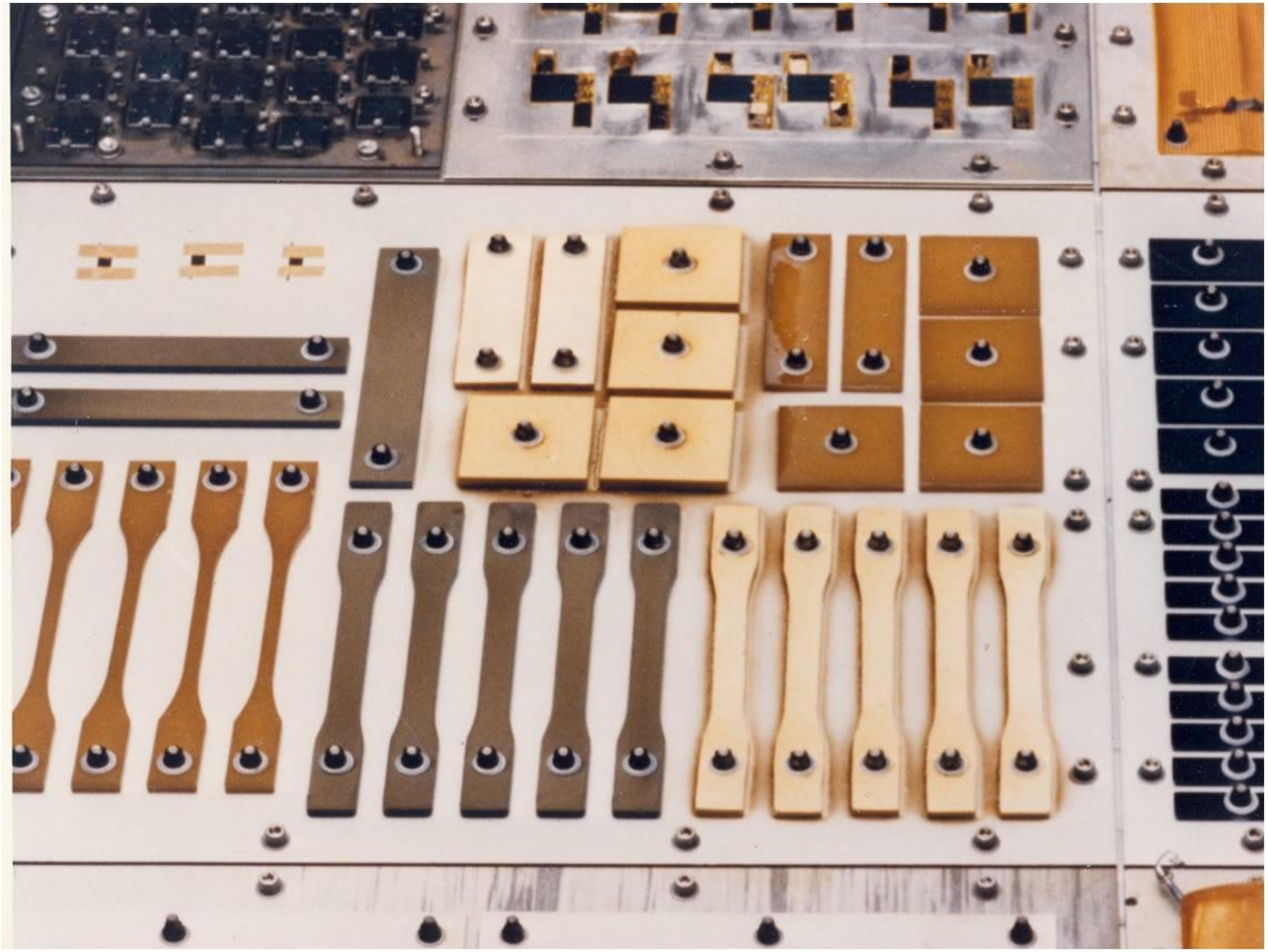
Under Mount

Kapton XC experienced a factor of 4 higher erosion rate under tension

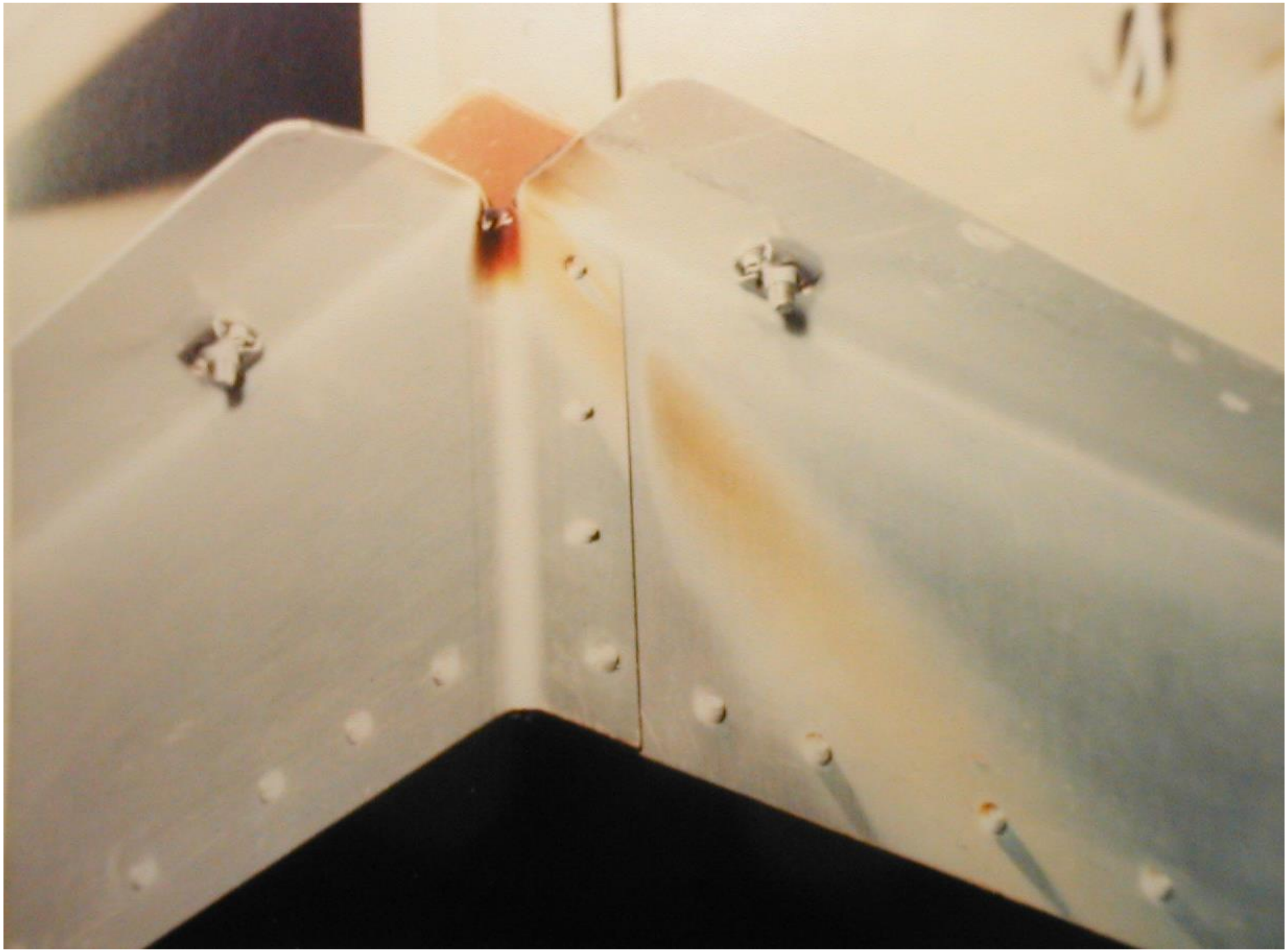
CONTAMINATION

Waste Water Dump Residue on Polished Plate Micrometeoroid and Debris Collector Experiment on MIR

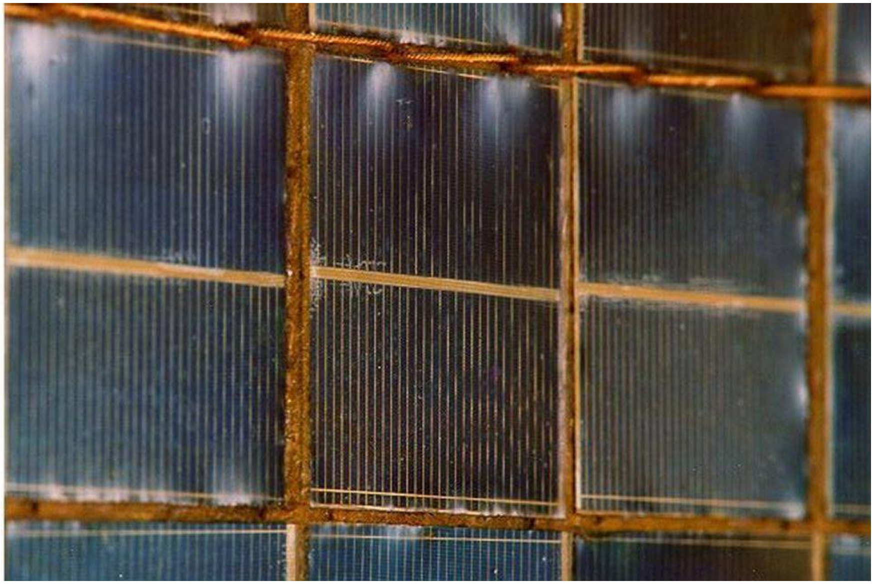
Silicone Contamination on LDEF Tray



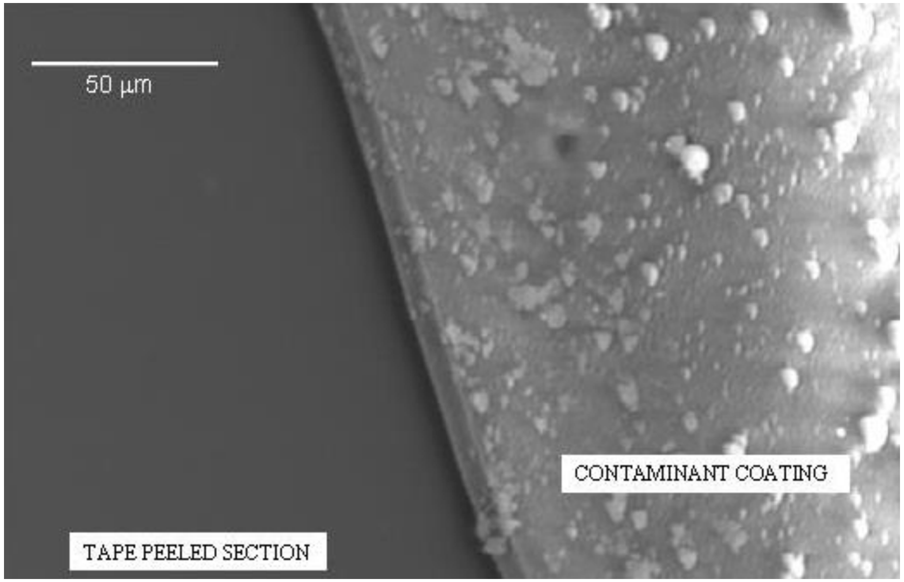
LDEF Experiment Tray



Oxidized Silicone Contamination on the MIR Solar Array After 10 Years in LEO



Frosty deposits on solar cell cover glasses

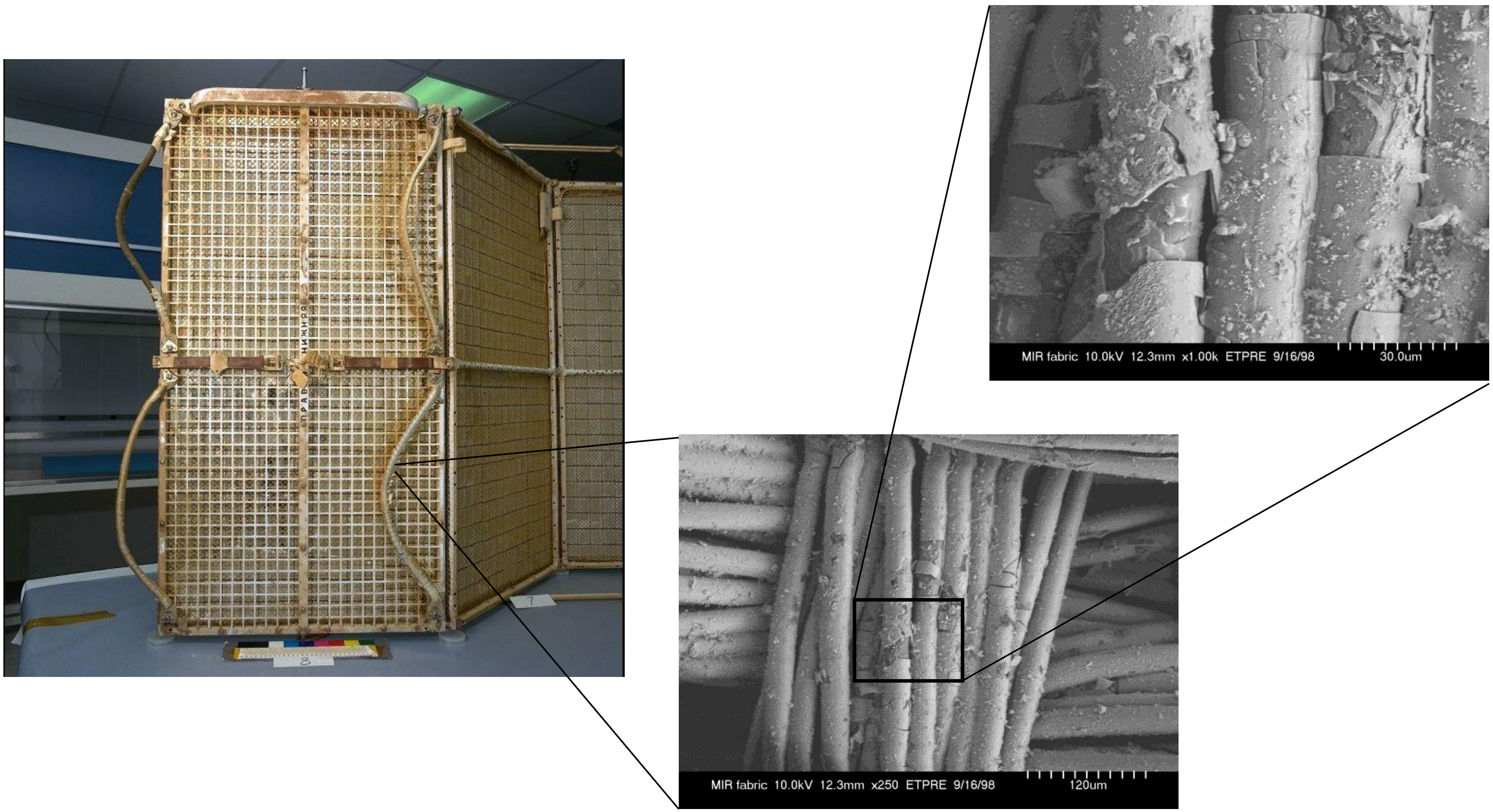


~ 4.6 micron thick silica deposits

Silicone Contamination on Mir PV Array Optical Solar Reflector (OSR)

Suture

Silicone Contamination on MIR Flexible Handhold Fabric Tape



Summary

Atomic Oxygen:

- Atomic oxygen is the most predominant specie in LEO
- Atomic oxygen is reactive and energetic enough to break chemical bonds in materials
- Reaction products with polymers and carbon containing materials are volatile (typically CO and CO_2)
- Metals and inorganics experience surface oxidation in some cases leading to shrinkage and cracking or spalling
- Atomic oxygen can thermalize on contact and scatter from surfaces leading to further reaction, which is dependent on the materials it contacts and geometry
- The effect that atomic oxygen has on a particular material on a spacecraft is dependent upon how much atomic oxygen arrives at the surface, atom energy, and can be affected by mechanical loading, temperature, and other components in the environment (UV radiation, charged particles…)

Summary

Contamination:

- Contamination can be as a result of actions of a nearby neighboring spacecraft or experiment, or by self contamination
- Contaminants can be fixed on a surface by UV radiation or atomic oxygen
- Contamination can cause detrimental changes in optical and thermal properties

Overall:

- Each situation is unique and for accurate prediction of degradation of a material or component, it should be tested or modeled in a configuration representative of how it will be used

Atomic Oxygen Team at NASA GRC in Environmental Effects and Coatings Branch, Materials and Structures Division:

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Publications:

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